

REMARKS

The timely filed Reply is in response to a Non-Final Office Action dated October 6, 2004. In the Office Action, Claims 1-16 were pending, and all claims were rejected. In this Reply, claims 1, 6 and 12 have been amended, and claim 2 has been cancelled. No new matter has been added.

In the Office Action, Claims 1-14 were rejected under 35 U.S.C. 103(a) as being unpatentable over U.S. Pat. No. 6,069,021 to Terashima et al. in view of a paper by Kumashiro et al. entitled "Epitaxial Growth of Rhombohedral Boron Phosphide Single Crystalline Films by Chemical Vapor Deposition". According to the Examiner, "it would have been obvious to form the boron phosphide buffer layer of Terashima et al. as taught by Kumashiro et al. in order to obtain the boron phosphide material taught in that reference." Claims 15-16 were rejected under 35 U.S.C. 103(a) as being unpatentable over the references as applied to claims 1-14, and further in view of Reif et al (U.S. Patent No. 4,579,609).

Before reviewing the cited art, Applicants will first review the claimed invention as now recited in amended claim 1, with underlines showing the added language. Amended claim 1 recites a semiconductor device, comprising a silicon (111) single crystal substrate; a single crystal epitaxial boron phosphide (BP) comprising layer disposed directly on the substrate, and a group III-nitride semiconductor epitaxial layer disposed directly on the BP layer. Thus, Applicants claim a single crystal group III-nitride semiconductor epitaxial layer (e.. GaN) disposed directly on an epitaxial single crystal BP buffer, the single crystal BP buffer layer being directly disposed on a silicon (111) single crystal substrate.

Applicants are clear when using the phrase "single crystal" regarding both the BP buffer and the group III-nitride semiconductor epitaxial layer. Paragraph 17 of Applicants' application notes the following:

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As used herein, the term "single crystal" as applied to both the BP comprising buffer layer and the group III-nitride layer refers to a layer which provides a full width half maximum (FWHM) X-ray ω -scan rocking curve of no more than 10 arc-min, more preferably less than 8 arc-min, and most preferably less than 7 arc-min.

Applicants also present data to demonstrate the single crystal results achieved and claimed herein. FIG. 2 is a low resolution X-ray diffraction (LRXRD) spectra of epitaxial BP grown on single crystal Si(111) showing a single phase BP (111) layer. FIG. 3 is a LRXRD spectra of GaN grown on a BP buffer layer on Si (111) at T= 850° C showing a single hexagonal phase GaN layer.

Applicants also teach how to obtain epitaxial single crystal BP on Si (111). For example, paragraph 28 includes the following teaching:

Remove of effectively all the native oxide on the silicon surface was determined to be an important process step prior to BP deposition. Optimal BP growth was found to occur when the Si substrate was cleaned in warm trichloroethylene(TCE)/acetone/methanol and etched for one minute in dilute HF, such as 1% HF. This is preferably followed by an *in-situ* hydrogen reduction (e.g. 4% H₂ in N₂) for ten minutes at or near the BP epitaxial growth temperature, such as at 1000° C for an 1100° C BP deposition process. The hydrogen reduction conditions are chosen to preferably remove the entire native oxide layer on the Si substrate remaining after the solution clean/etch described above.

Terashima discloses a method of growing a group III nitride semiconductor crystal layer. The method begins with growing a first buffer layer composed of boron phosphide (BP) on a silicon single crystal substrate by a vapor phase growth method at a temperature of not lower than 200 degrees C and not higher than 700 degrees C. A second buffer layer composed of BP is then grown on the first buffer layer by a vapor phase growth method at a temperature of not lower than 750 degrees C and not higher than 1200 degrees C. A crystal layer composed of group III nitride semiconductor crystal represented by general formula $\text{Al}_p\text{Ga}_q\text{In}_r\text{N}$ (where $0 \leq p \leq 1$, $0 \leq q \leq 1$, $0 \leq r \leq 1$, $p+q+r=1$) is then grown on the second buffer layer by a vapor phase growth method. A semiconductor device incorporating the group III nitride semiconductor crystal layer is provided.

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Terashima repeatedly teaches that it is necessary to include an amorphous or polycrystalline BP layer on the silicon substrate before depositing a more crystalline BP layer (deposited at high temperature; never referred to as being single crystal) because it is not possible to grow a high quality BP crystal directly on a single crystal substrate due to lattice mismatch between the Si substrate and the BP buffer.

For example, col. 2, lines 31-42 discloses the following:

A major obstacle to progress has been the lattice mismatch between silicon single crystal and group III nitride semiconductor crystal owing to the difference between their lattice constants. For example, the lattice constant of silicon single crystal is 5.431 .ANG. while the lattice constants of cubic system gallium nitride (GaN), aluminum nitride (AlN) and indium nitride (InN) are 4.51 .ANG., 4.38 .ANG. and 4.98 .ANG., respectively. Based on the lattice constant of silicon single crystal, therefore, the lattice constants of GaN, AlN and InN differ therefrom by 8-19%. *This has prevented the formation of a high-quality group III nitride semiconductor crystal layer by direct growth on a silicon single crystal substrate.* (italics for emphasis)

Similarly, col. 3, lines 20-33 discloses the following:

In other words, the conventional technology of using a vapor phase growth method to grow BP crystal directly on a silicon single crystal substrate at a high temperature of 850.degree. C. or higher and then growing a group III nitride semiconductor crystal layer thereon is incapable of forming a buffer layer consisting of flat and continuous BP. *This makes it impossible to grow a continuous group III nitride semiconductor crystal layer of good Xi quality on the buffer layer.* Moreover, when BP crystal is grown on the surface of a silicon crystal substrate by this conventional method, the difference between the lattice constants of the two crystals makes the BP crystal highly susceptible to peeling. (italics for emphasis).

The two layer buffer structure is disclosed by Terashima as solving the lattice mismatch problem:

When vapor phase growth is effected on the single crystal substrate at a temperature in the range of 200 degree C.-700.degree C. as described in the foregoing, *a first buffer layer composed of polycrystalline or amorphous BP is formed which relieves strain arising relative to the single crystal substrate owing to difference between lattice constants.* Then when vapor phase growth is effected on the first buffer layer at a temperature in the range of 750 degree C.-1200 degree C., a single crystal second buffer layer is continuously formed. A crystal layer composed of high-quality group III nitride semiconductor is formed on the second buffer layer. (italics for emphasis).

Terashima also includes a comparative example to show high quality BP cannot be grown on Si. Col. 15, lines 43-56 discloses the following:

LEDs were fabricated without providing the first buffer layer on the Si single crystal substrate. Instead, the same halide VPE method as in Example 1 was conducted at 890.degree. C. to deposit an approximately 2 .mu.m-thick buffer layer composed of BP directly on a Si single crystal substrate like that of Example 1.

However, a continuous BP buffer layer could not be formed by directly depositing BP crystal on a Si single crystal substrate at a high temperature in this manner. All that was obtained was pyramid-like islands of about 2 .mu.m thickness scattered over the Si single crystal substrate surface. Normal group III nitride semiconductor crystal layers usable to configure LEDs could therefore not be formed.

Based on the above, it is clear that Terashima strongly teaches away from Applicants' claimed device which includes an epitaxial single crystal BP buffer layer disposed directly on the silicon substrate. Epitaxy is clearly lost by Terashima by the intervening low temperature BP layer on the Si (111). Accordingly, the high temperature BP layer disposed on the low temperature amorphous or polycrystalline BP layer is clearly not epitaxial, and as a result cannot be single crystal.

The Examiner attempts to use Kumashira to make up for the above-described deficiencies of Terashima. As noted above, the Examiner asserts "it would have been obvious to form the boron phosphide buffer layer of Terashima et al. as taught by Kumashiro et al. in order to obtain the boron phosphide material taught in that reference." Applicants respectfully disagree with the Examiner's assertion.

Kumashiro was published in 1997 and discloses rhombohedral *boron subphosphide* ($B_{12}P_2$) single crystalline films grown at 1100°C by thermal decomposition of a diborane/phosphine/hydrogen (B_2H_6 - PH_3 - H_2) gas mixture. The crystal quality and orientation of the films, determined by reflection high-energy electron diffraction and X-ray diffraction, are reported to be strongly influenced by the flow rates of reactant gases. The epitaxial relationships

are $B_{12}P_2$ (1120)[0001] \parallel Si (100)[010],[011] and $B_{12}P_2$ (1011)[1210], [1014] \parallel Si (100)[010], of eight- and twofold symmetry, respectively. The distribution of the two planes in the films changes along the growth direction. The epitaxial relationship on the Si (111) surface is $B_{12}P_2$ (1010)[0001] \parallel Si (111)[110]. The $B_{12}P_2$ (0221) plane grows near the Si substrate, but the existence of the (1010) plane increases during the crystal growth process. (*italics for emphasis*)

The only buffer layer Kumashira discloses is boron subphosphide ($B_{12}P_2$) other than in the Introduction where it is noted that BP has a zinc-blend structure while boron subphosphide ($B_{12}P_2$) has a quite distinct rhombohedral structure. Although Kumashira refers to the boron subphosphide ($B_{12}P_2$) layer as being "single crystal", at least with respect to $B_{12}P_2$ grown on a Si (111) substrate (a Si (111) substrate is what is claimed by Applicants), his data clearly shows otherwise. Figure 9, for example, shows X-ray diffraction patterns from boron subphosphide ($B_{12}P_2$) films grown by Kumashira. The presence of multiple diffraction peaks, several having significant amplitude, clearly evidences a polycrystalline boron subphosphide ($B_{12}P_2$) layer, not a single crystal one. Accordingly, at least with respect to Si (111) substrates, Kumashira teaches a polycrystalline boron subphosphide ($B_{12}P_2$) layer.

The proposed combination of Terashima with Kumashiro does not provide Applicants' claimed invention. Neither reference discloses formation of an epitaxial single crystal BP (or boron subphosphide ($B_{12}P_2$) in the case of Kumashiro) layer directly on Si (111). Terashima discloses an amorphous BP layer formed at low temperature over a Si substrate and a crystalline (non-epitaxial) BP layer disposed on the amorphous BP layer, while Kumashiro discloses a polycrystalline boron subphosphide ($B_{12}P_2$) layer on Si (111). Applicants note that if Kumashiro's single step boron subphosphide ($B_{12}P_2$) buffer process (published in 1997) were truly useful for

BP on Si (111), the complex dual buffer layer process developed, disclosed and patented by Terashima about 2 years later (filed Feb. 9, 1999) would have been totally unnecessary.

Moreover, Terashima and Kumashiro are not combinable because Terashima discloses BP while Kumashiro relates to $B_{12}P_2$, not BP. As correctly noted by Kumashiro, BP has a zinc-blend structure while boron subphosphide ($B_{12}P_2$) has a quite distinct rhombohedral structure. The difference in crystal structure between BP (zinc-blend structure) and $B_{12}P_2$ (rhombohedral structure) is further proof that Kumashiro paper relating to ($B_{12}P_2$) is not relevant to Terashima or the claimed invention which both relate to BP.

There is also no motivation to combine Kumashiro and Terashima, in fact Terashima strongly teaches away from such a combination. As noted above, Terashima discloses that "conventional technology of using a vapor phase growth method to grow BP crystal directly on a silicon single crystal substrate at a high temperature of 850 degrees C or higher and then growing a group III nitride semiconductor crystal layer thereon is incapable of forming a buffer layer consisting of flat and continuous BP". Kumashiro's results on (111) Si are clearly polycrystalline as shown in Fig. 9, which would support the teaching in Terashima that boron subphosphide ($B_{12}P_2$) requires additional processing analogous to BP on Si (111), where an initial BP amorphous/polycrystalline layer must be deposited on Si (111) to get a high quality BP layer.

Accordingly, Applicants submit that amended claim 1 and claims dependent thereon are patentable over the cited art. Claim 6 (LED) and claim 12 method include analogous limitations to those recited in amended claim 1 and are patentable along with their respective dependent claims for the same reasons as noted above relative to amended claim 1.

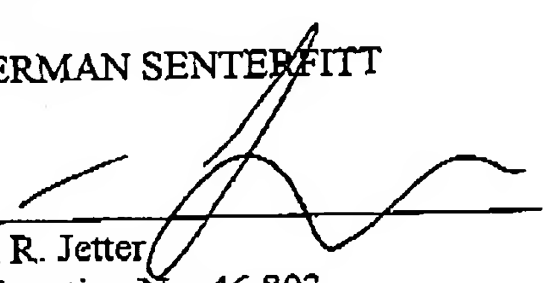
Applicants have made every effort to present claims which distinguish over the cited art, and it is believed that all claims are now in condition for allowance. However, the Examiner is

invited to call the undersigned (at 561-671-3662) if it is believed that a telephonic interview would expedite the prosecution of the application to an allowance. The Commissioner for Patents is hereby authorized to charge any deficiency in fees due with the filing of this document and during prosecution of this application to Deposit Account No. 50-0951.

Respectfully submitted,

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Date: December 23, 2004



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Docket No. 5853-414